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The seasonal evolution of the stratosphere in the northern hemisphere.

by

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THE SEASONAL EVOLUTION OF THE STRATOSPHERE IN THE NORTHERN HEMISPHERE

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THE SEASONAL EVOLUTION OF THE STRATOSPHERE IN THE NORTHERN HEMISPHERE

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ABSTRACT. Isentropic maps of Ertel's potential vorticity are used to describe the seasonal evolution of the mid stratosphere in the northern hemisphere during the year 1980/81. Systematic changes in the circulation are noted and their causes considered. The meridional transport of air due to planetary-scale disturbances is outlined.

1. INTRODUCTION

Our aim in this paper is to give a brief description of the seasonal evolution of the circulation in the mid stratosphere of the Northern Hemisphere, noting in particular periods when large-scale disturbances to the flow bring about material exchange between latitudes.

The movement of air, or transport, and photochemistry change the distribution of trace gases in the stratosphere. Simplified numerical models of these processes are often based on a zonal average of the governing equations (see Brasseur and Solomon, 1984, for a review). Such averaging may be inappropriate when the flow is strongly disturbed, i.e. when it is far from being symmetric about the pole. One reason is that when the intense cyclonic vortex of the winter stratosphere is displaced from the pole by large-scale disturbances, the basic physical property that its inner portion retains for a few weeks the same body of air is obscured by a zonal average.

We shall infer meridional transport associated with systematic changes in the stratospheric circulation by using synoptic maps of Ertel's potential vorticity, Q. For the large-scale flow of the stratosphere, Q can be expressed approximately as

$$Q \approx - g(\zeta+f)\partial\theta/\partial p \qquad (1)$$

where g is the acceleration due to gravity, ζ is the vertical component of relative vorticity, f is the Coriolis parameter, θ is potential temperature and p is pressure. Q is conserved for adiabatic, frictionless flow, as is θ. Then, contours of Q plotted on a

quasi-horizontal surface of constant θ are material lines which can be used to trace the movement of air. Q is also a dynamically active quantity in that it modifies the flow as it is advected. In principle, winds and other meteorological fields can be derived from the three-dimensional distribution of Q, provided the flow is "in balance" (e.g. in geostrophic balance) and boundary conditions are available. Hoskins et al. (1985) elaborate on these properties and give examples of their utility.

Our discussion is based on maps of Q for the 850K isentropic surface, which lies near 10 mb in the mid stratosphere where the flow can be taken as conservative for a week or so (the radiative timescale is about 20 days). This level can be used to illustrate transport mechanisms operating in the stratosphere as a whole, but accurate calculations would need to treat variations in height of dynamical and radiative processes. We cannot infer directly from maps of Q the transport of a trace gas over a season because Q is not conserved for this long. We can, however, use such maps to study transport over shorter, dynamically active periods (lasting a week, say) and gain some understanding of what the cumulative effects might be if disturbances persist.

The circulation in the stratosphere in mid winter is dominated by a huge cyclonic vortex covering most of a hemisphere. The vortex is created by radiative cooling, and is characterised by strong winds and a large meridional gradient of Q at mid latitudes (as we show later). From the dynamical theory of large-scale Rossby waves, it is known that a gradient of Q acts as a restoring force on meridional displacements of strings of air parcels (the argument given by Holton, 1979, page 166, must be adapted if winds vary in height, longitude and latitude). This gradient is therefore a barrier to horizontal transport into the centre of the vortex by large-scale disturbances. While the vortex is strong and large, horizontal transport is confined to low latitudes where winds and the gradient of Q are weak (Plumb and Mahlman, 1987) though air parcels may drift slowly into the vortex as a result of radiation. For a trace gas created photochemically at low latitudes to spread more rapidly over the winter hemisphere, the vortex must be broken down. We shall outline how this happens and suggest an explanation of why it does.

The paper is laid out as follows: Section 2 contains a summary of the data used in this study and of our method of analysis. We describe the synoptic evolution in the stratosphere during the northern winter of 1980/81 in section 3, where we focus on the systematic changes in the circulation, suggest possible causes for them, and infer broadly how transport varies through the year. Concluding remarks are in section 4.

2. DATA AND METHOD OF ANALYSIS

The data used in this study were obtained mainly from a stratospheric sounding unit (SSU) on board the satellite NOAA-6. Pick and Brownscombe (1981) describe the instrument. It is a nadir sounding radiometer which

scans across the orbital path giving almost global coverage. The measuring channels of the SSU have weighting functions centred in the stratosphere near 15, 5 and 1.5 mb. The vertical resolution is about 10 km; after fields are smoothed the horizontal resolution is limited to about wave-number 12 in the meridional (pole-to-pole) and zonal directions.

Details of the analysis and of the calculation of isentropic maps of Q are given by Clough et al. (1985). Briefly, thicknesses are derived from radiances by statistical regression. Fields of geopotential height are produced by adding the thicknesses to a global analysis of geopotential height at 100 mb provided by the National Meteorological Center (Washington). Winds and temperatures are calculated using the geostrophic and hydrostatic approximations, and Q is calculated by differentiating and interpolating these fields.

3. SEASONAL EVOLUTION IN THE NORTHERN HEMISPHERE, 1980/81

3.1 Description of synoptic maps

We now show a selection of maps of Q and horizontal winds on the 850K isentropic surface for the Northern Hemisphere during the period 1980 to 1981. We describe changes in the distribution of Q and associated changes in the circulation that occurred during a sequence of minor and major warmings, and comment on the transport taking place.

The first strong warming of the winter is of the type known as a Canadian warming because warm air is advected over Canada. Its evolution is similar to the one in December 1981 discussed by Clough et al. (1985). At the beginning of November 1980, a westerly vortex lies roughly symmetrically over the North Pole. Q is a maximum near its centre and rapidly decreases towards low latitudes. As the ensuing disturbance develops, low Q is advected north eastwards from low latitudes. The distribution of Q and winds on 23 November is shown in Fig. 1. An island of low Q is cut off from similar values of Q at low latitudes by a closed anticyclonic circulation that forms around it. (Because material lines do not break, there will be filaments of low Q, too thin to be resolved, connecting the two regions unless dissipation has wiped them out.) The westerly vortex is elongated and displaced from the pole, and a tongue of high Q stretches out from the vortex around the anticyclone.

The quasi-horizontal advection of Q gives a good indication of transport in this case. The disturbance develops in about a week and changes in temperature are modest compared with those found during major warmings, so the non-conservative effect of radiation does not stop the contours in Fig. 1 from being regarded as material lines. Also, the pattern shown extends through a deep layer of the stratosphere and therefore the vertical resolution of the measurements is not a limitation.

The meridional displacements of air parcels during the Canadian warming are, for the most part, only temporary. In late November, the island of low Q shown in Fig. 1 is drawn across the polar cap back into low latitudes, slicing through the tongue of high Q in the process. This tongue is eventually reabsorbed by the main vortex which moves back over the pole and becomes roughly symmetric about it.

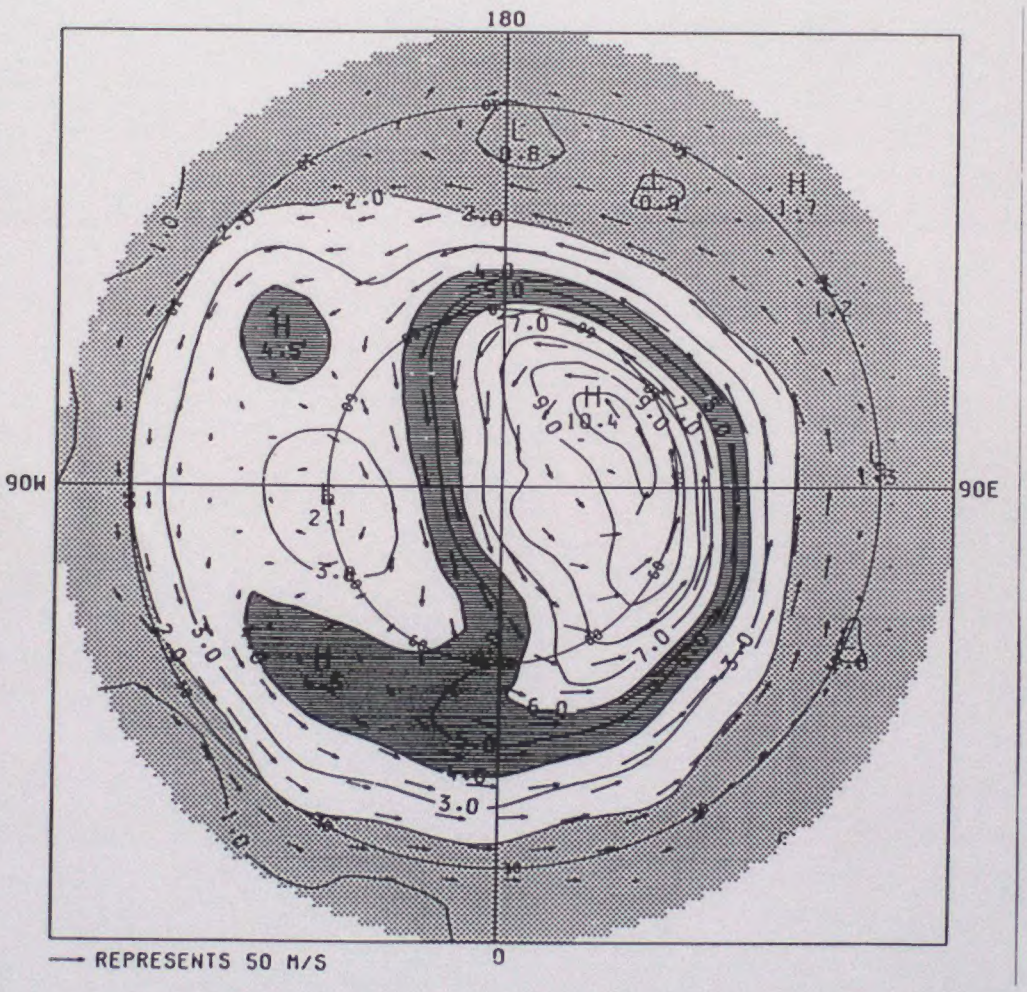

Figure 1. Polar-stereographic map of Ertel's potential vorticity, Q, and winds on the 850 K isentropic surface for 23 November 1980. The units are 10^{-4} K m^2 kg^{-1} s^{-1}. The light shading is for values less than 2 and heavy shading is for values between 4 and 6 in the above units. The frame surrounding the figure is tangent to latitude 20°N.

During December, the westerly vortex is disturbed only weakly, being roughly symmetric about the pole as shown in Fig. 2 for 2 January 1981. It continues to strengthen owing to radiative cooling in the polar night. This quiescent interlude is ended by the build-up of strong disturbances in January, a prelude to a major stratospheric warming in early February (described by Labitzke et al., 1981). An anticyclone (the so-called Aleutian High) builds in the stratosphere and, unlike its behaviour during the Canadian warming, it persists near the dateline. Systematic changes ensue in the structure of the circulation; in particular the westerly vortex shrinks rapidly. Fig. 3 shows the distribution of Q and winds on 1 February 1981. Broadly, in

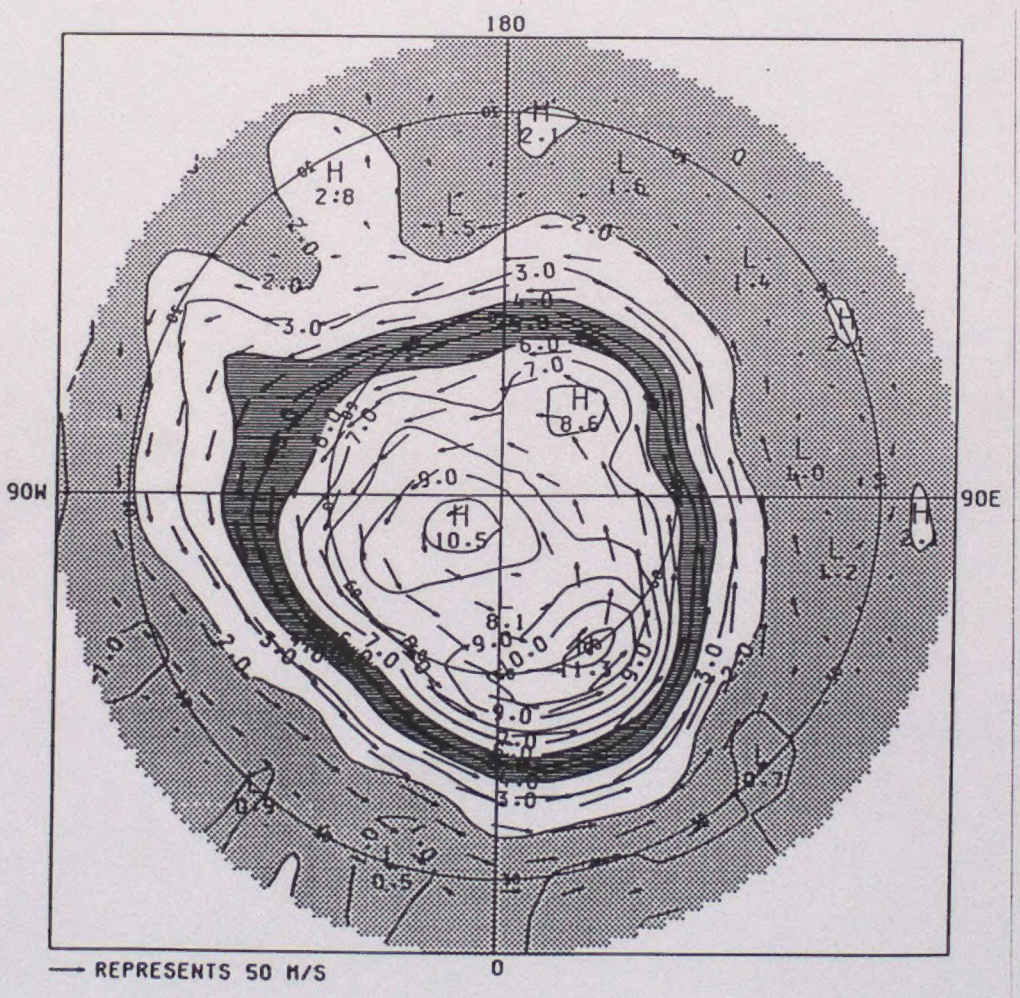

Figure 2. As Fig. 1 but for 2 January 1981.

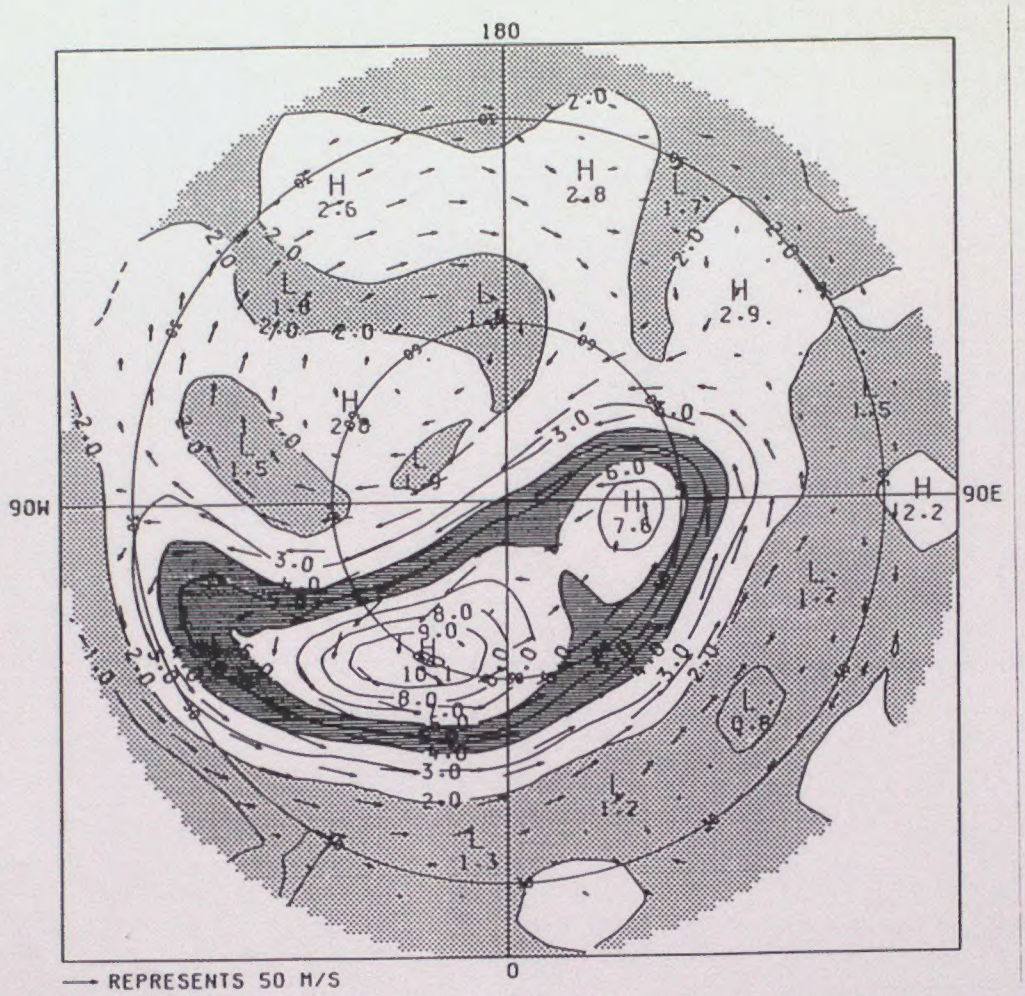

Figure 3. As Fig. 1 but for 1 February 1981.

the top half of the figure is air with low Q originally from low latitudes; in the bottom half is polar air with high Q. Errors in analysis probably account for the jumble of Q contours in the anticyclone; gradients are weak there and a small error in calculating Q can make a big difference to a contour's position. The Aleutian High draws air with high Q away from the cyclone towards low latitudes - notice the tongue of high Q being drawn out near 90°W, 40°N. The limited resolution of the measurements allows us only a blurred view of the process, and so we are unable to witness the fate of the tongue of high Q.

The capturing of high Q by the persistent Aleutian High seems to be an important mechanism (radiation is another) for breaking down the large cyclonic vortex that develops in the stratosphere in early winter. McIntyre and Palmer (1983) noted this possibility and discussed some of the possible dynamical implications.

The area covered by the cyclone is much smaller in Fig. 4, the synoptic map for 4 March 1981, than it is in Fig. 3, and values of low Q at the centre of the anticyclone have increased. By mid March, the flow is almost zonally symmetric apart from a weak cyclone displaced from the pole, as is shown by Fig. 5 for 19 March 1981. Q is nearly uniform at high latitudes and winds are correspondingly weak. At lower latitudes, a westerly jet coincides with a zone where the gradient of Q is larger. The residue of the cyclone slowly disappears, and easterly winds eventually replace westerlies in the mid and upper stratosphere. This region is cut off from large-scale, tropospheric disturbances by the easterlies (Charney and Drazin, 1961), and the transport in the hemisphere is limited to a slow meridional circulation driven by radiation.

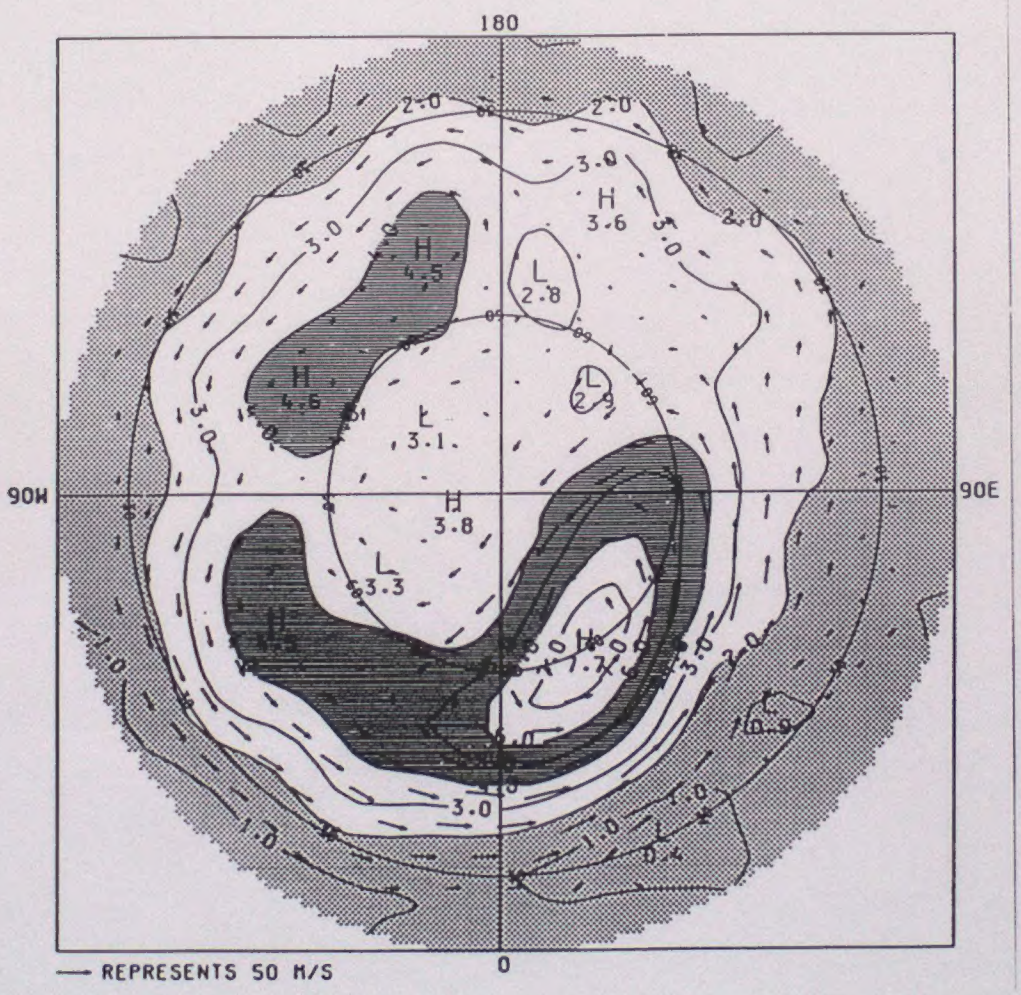

Figure 4. As Fig. 1 but for 4 March 1981

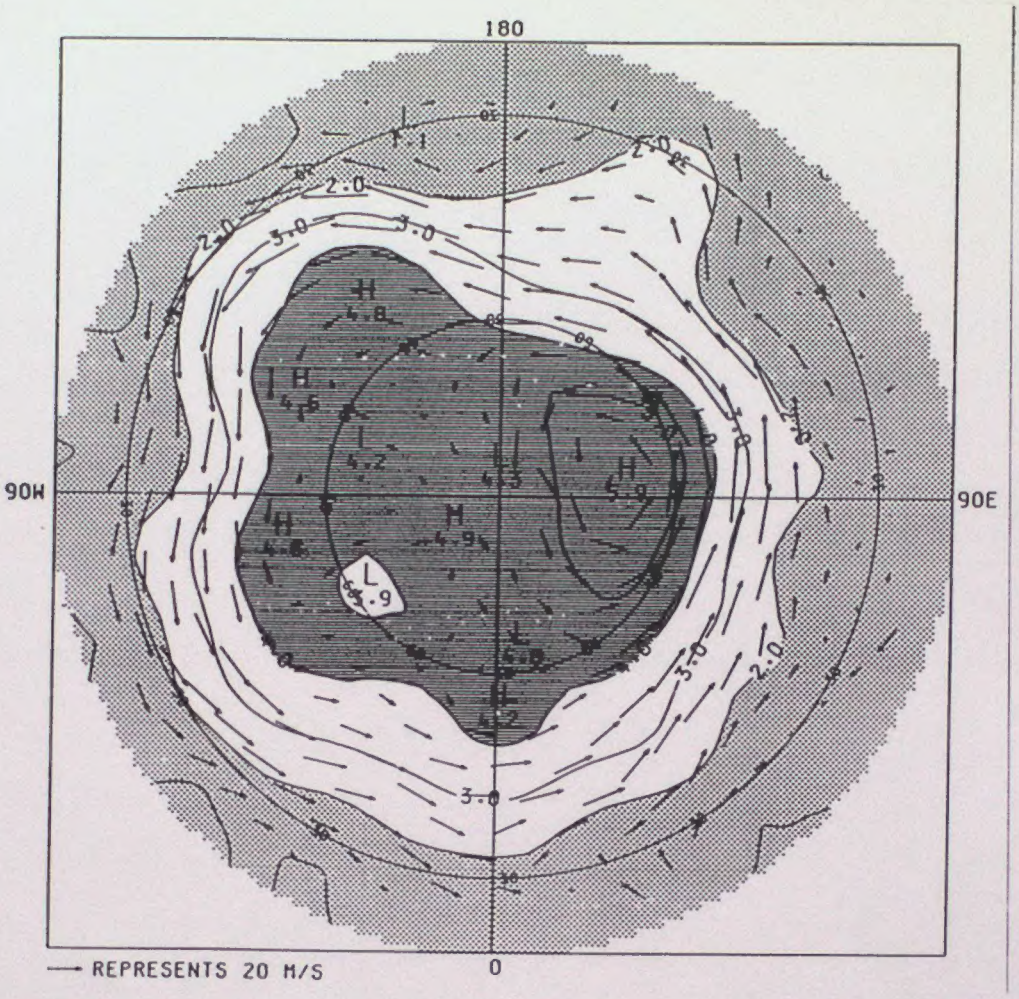

Figure 5. As Fig. 1 but for 19 March 1981.

3.2 Non-conservative processes governing systematic changes in the stratosphere

As we have seen, once the Aleutian High is established the large cyclonic vortex in the stratosphere starts to break down rapidly. The distribution of Q is changed systematically both by advection of material on an isentropic surface and by non-conservative processes which create or destroy Q. In this section, we consider what these processes might be.

We may summarize the systematic changes in the distribution of Q by computing the area of an isentropic surface, A(Q), where the value of potential vorticity is bigger than Q. Doing this for a number of values of Q, we are able to estimate the size of the cyclone by following the prescription given by McIntyre and Palmer (1984): in brief, find the value of Q at which there is a sharp change in dA/dQ, then the area surrounded by the contour corresponding to that value is

roughly the area covered by the cyclonic circulation. The method relies on the observed property that gradients of Q in the stratosphere are strong in the cyclone and weak in an anticyclone. For instance, the contour labelled '3.0' in Fig. 3 roughly circumscribes the cyclone, and the difference between A(4) and A(3) is much smaller than that between A(3) and A(2). A diagnostic based on averaging around latitude circles does not reveal systematic changes as clearly as A(Q) does, for such a quantity would vary as the cyclone moved about the polar cap even if the cyclone's structure remained the same.

The evolution of A(Q) may also be used to deduce on average where and when non-conservative processes are important. Our discussion here will be qualitative but it is supported by calculations that we have done (to be reported), and also by the work of Butchart and Remsberg (1986) and of Butchart (1987).

A(Q) is constant if the following hold: (1) radiation and friction can be neglected; (2) the flow is fully resolved; (3) on average, the large-scale flow is non divergent. The reason is that a contour of Q is a material line if (1) and (2) hold, and the area enclosed by a material line is constant in a non-divergent flow. We find (in work to be reported) that assumption (3) is acceptable in a qualitative discussion (but not when accuracy is required). So assumption (1) or (2) or both must be invalid since A(Q) changes with time, as is evident from the synoptic maps introduced earlier.

Radiation and friction change A(Q) irreversibly, i.e. in a time-oriented way. Changes in A(Q) through loss of resolution may be reversible or irreversible depending on the dynamics involved. McIntyre and Palmer (1983, 1984) propose that extreme buckling of Q contours, such as that shown in Fig. 1, will irreversibly mix Q on an isentropic surface to small, unresolved scales in the horizontal. As a result of mixing, A(Q) will decrease for high Q and increase for low Q, perhaps accounting for regions in the stratosphere where the gradients of Q are weak (e.g. near the Aleutian High in Fig. 3). The effects of such mixing have yet to be quantified directly. Using a reasonably accurate radiation scheme (Shine, 1987), we have estimated the rate of change of A(Q) due to radiation at different times of the year (paper in preparation). We shall summarize our findings here, but we stress that the calculations are liable to very large errors owing to the limited resolution of the observations on which they are based.

Fig. 6 shows, for various values of Q, the evolution of A(Q) for the 850 K isentropic surface in the Northern Hemisphere from June 1980 to June 1981. Also plotted is one curve (dashed) for an annual cycle in the Southern Hemisphere. This curve is displaced along the time axis by six months so that corresponding seasons in the two hemispheres may be compared. There is a marked seasonal variation in A(Q) due to the seasonal variation in solar heating. The build up of the cyclone in autumn is reflected by the increase in A(Q) for high values of Q. The cyclone continues to build and areas continue to increase over the course of the Canadian warming. The flow is most disturbed at the end of November, and inadequate resolution accounts for rapid changes in A(4). (Values of Q are given in the units used to plot contours on the synoptic maps.) The disturbance, though strong, does not lead to much

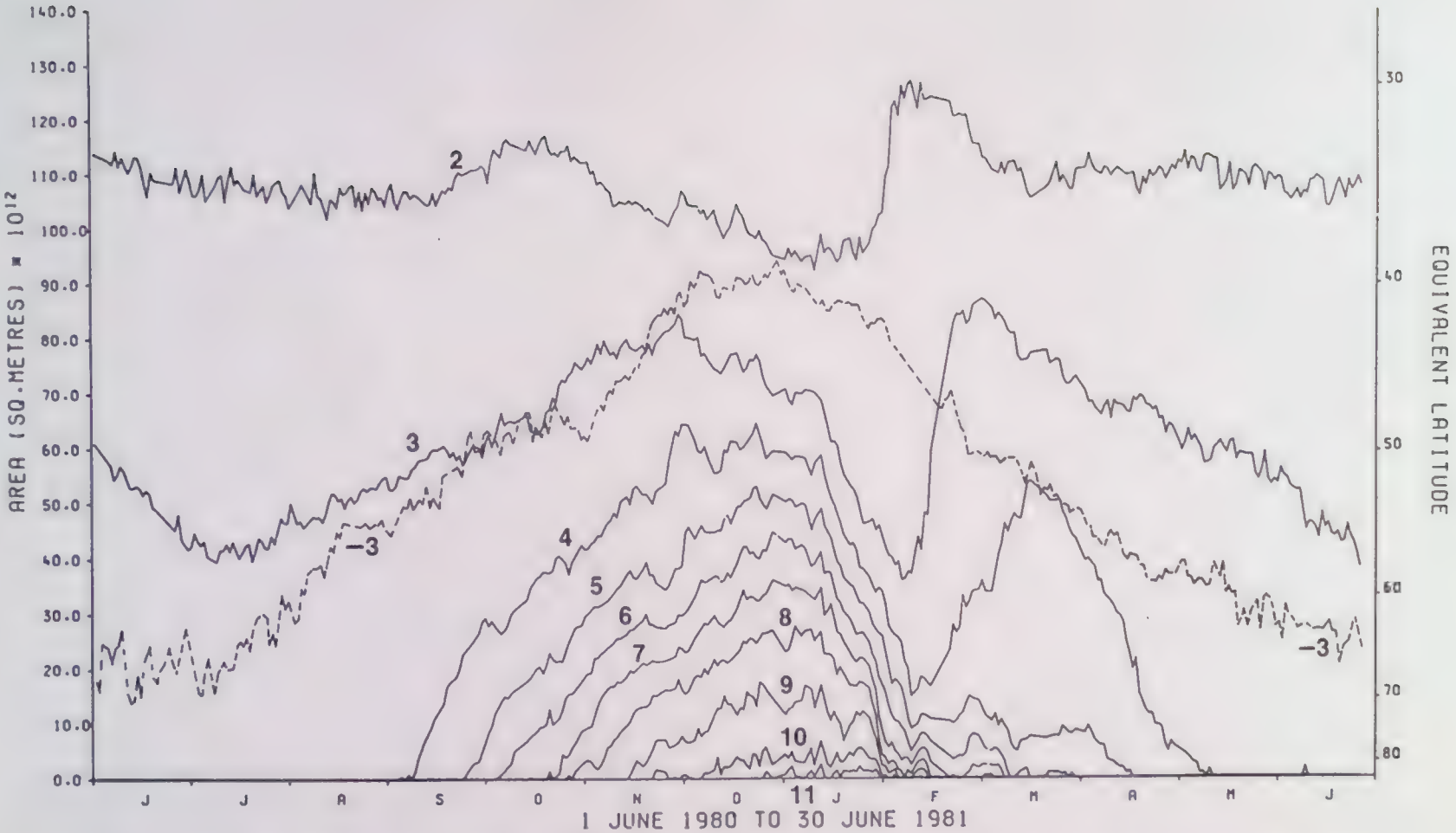

Figure 6. Graphs of areas A(Q) ($km^2 \times 10^6$) as described in the text. Each curve is labelled with the corresponding value of Q in units of 10^{-4} K m^2 kg^{-1} s^{-1}. The continuous curves are for the Northern Hemisphere from 1 June 1980 to 30 June 1981 and the dashed curve is for the Southern Hemisphere from 1 December 1980 to 30 December 1981 (displaced by six months on the time axis). The equivalent latitude, marked on the right hand axis, is calculated as the latitude circle that encloses the area marked on the left hand axis.

erosion of the cyclone because an area of high Q that becomes separated from the cyclone eventually recombines with it. Radiation is apparently more than enough to offset any effect on Q of mixing during the Canadian warming. Clough et al. (1985) found the same for the Canadian warming of 1981.

The vortex is largest at the beginning of January; in Fig. 6, most of the A(Q) reach their maximum values then. As the Aleutian High intensifies, areas decrease rapidly. During January, A(3) is a rough measure of the size of the cyclone (based on the argument given above), and Fig. 6 shows that it almost halves its size in the month. For the less disturbed Southern Hemisphere, A(-3) is about twice A(3) a month after mid winter.

Persistent disturbances take the stratosphere away from a state near to radiative equilibrium and lead to systematic changes in A(Q). Our calculations indicate that radiation reduces the high Q in the cyclone after mid winter (by reducing the stability of the air), but it cannot fully account for the rapid decreases in areas in January. We ascribe the remainder to errors in these calculations, and to high Q being lost to view, e.g. by being drawn into narrow tongues around the southern flank of the Aleutian High. McIntyre and Palmer (1983) noted that Q could apparently disappear in this way. Such a tongue is shown at inception in Fig. 3. Our observations have inadequate resolution to show its elongation and narrowing beyond this stage during January, but a simulation that we made using a numerical model with much better resolution does.

The increases in areas during February and March, on the other hand, can be accounted for by radiation; if our calculations are accurate, the process of mixing, mentioned above, does not need to be invoked. Values of Q at the centre of the anticyclone increase (compare Fig. 4 with Fig. 3) as warm air cools and sinks through isentropic surfaces bringing down higher values of Q. By diminishing the local anomaly in Q, radiation inhibits the growth of the anticyclone, restraining its erosion of the cyclone. The jet at low latitudes that we noted in Fig. 5 is presumably generated by Coriolis forces acting on a poleward and downward circulation driven by the cooling at high latitudes.

We conclude that the formation of weak gradients of Q in the stratosphere - as manifested in the big difference between A(2) and A(3) that develops after mid winter - is a consequence of (1) radiation acting on a highly asymmetric flow, and (2) failure to resolve Q fully e.g. in narrow tongues of high Q.

4. CONCLUSIONS

Transport of material in the stratosphere is rapid when large-scale disturbances develop in winter. Air from low latitudes is drawn polewards and air from high latitudes is drawn equatorwards as a growing anticyclone displaces the westerly vortex from the pole. An example of this exchange occurs during the strong Canadian warming of early winter 1980/81. But the displaced air mostly returns to its

original latitude as this disturbance decays. There is little net effect on the distribution of potential vorticity, Q, and hence on the circulation. Afterwards, the cyclone continues to intensify as a result of radiative cooling. Strong gradients of Q develop which inhibit the large-scale displacement of air across the gradient, isolating the air in the inner portion of the cyclone.

Permanent exchange of air between latitudes occurs once the so-called Aleutian High becomes a persistent feature, just after mid winter in 1980/81. The air circulating within the cyclone remains displaced from the pole, and air towards its edge is drawn into low latitudes by the anticyclone. Associated with this advection is a loss of high Q by the cyclone which consequently shrinks, making way for air originally from low latitudes to encroach into polar latitudes.

The persistence of the Aleutian High leads to systematic changes in the distribution of Q in the stratosphere, as is evident from the evolution of the areas on an isentropic surface where Q exceeds specified values. There are also systematic changes in the circulation. After mid winter, the areas decrease for high values of Q. We suggest that this might be accounted for by radiation, and failure to resolve Q, e.g. in tongues of high Q which extend around the Aleutian High. Increases in areas for low values of Q are apparently caused by radiation. Strong cooling over the polar cap after a major warming results in air moving along and sinking through isentropic surfaces which would redistribute a trace gas whose concentration varied in space. The cyclone stays off the pole and radiation gradually weakens it during spring. Once easterly winds replace westerlies, large-scale disturbances are trapped in the troposphere, and transport occurs in a slow meridional circulation driven by radiation.

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